

# Excluding Light Asymmetric Bosonic Dark Matter

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We argue that current neutron star observations exclude asymmetric bosonic non-interacting dark matter in the range from 2 keV to 16 GeV, including the 5–15 GeV range favored by DAMA and CoGeNT. If bosonic WIMPs are composite of fermions, the same limits apply provided the compositeness scale is higher than  $\sim 10^{12}$  GeV (for WIMP mass  $\sim 1$  GeV). In case of repulsive self-interactions, we exclude large range of WIMP masses and interaction cross sections which complements the constraints imposed by observations of the Bullet Cluster.

PACS numbers: 95.35.+d 95.30.Cq

*1. Introduction.* An appealing solution to the dark matter (DM) problem is offered by Weakly Interacting Massive Particles (WIMPs) emerging in many theories beyond the Standard Model (SM). However, WIMPs are very difficult to detect, and therefore little is known about their properties. Experimentally, the situation is rather unclear (see e.g. limits from CDMS [1]), with DAMA [2] and CoGeNT [3] suggesting the existence of a light WIMP with a mass around  $\sim 10$  GeV.

Apart from direct searches, constraints on WIMPs can be set by observations of compact objects such as white dwarfs and neutron stars [4–12]. These constraints can be grouped in two types. The first type targets WIMPs that can annihilate inside the star producing heat that can change the thermal evolution of the star [5]. WIMPs of this type can arise in supersymmetric extensions of the SM (see [13] and references therein), or in Technicolor models [14]. Constraints of the second type target asymmetric DM models. In these models the annihilation of DM in the present-day Universe is impossible because only particles, and no anti-particles (hence the term “asymmetric”) remain [15–19]. An additional bonus in these models is that the asymmetry of WIMPs might be linked through sphalerons with the baryon asymmetry [16, 18], which can explain the today’s ratio  $\Omega_{DM}/\Omega_B \sim 5$  provided the WIMP has a mass around 5 GeV. Note that this value is not far from the one suggested by DAMA and CoGeNT. In view of this coincidence, the models with WIMP masses in the GeV range have become quite popular.

Since in the asymmetric DM models WIMPs cannot annihilate, if a large number of them is accreted during the lifetime of a neutron star, they may collapse forming a small black hole inside the star that eventually destroy the latter. Therefore the existence of old neutron stars can impose constraints on the properties of asymmetric WIMPs. In fact, in the case of fermionic asymmet-

ric WIMPs with a spin-dependent cross section, these constraints are competitive to direct DM search experiments [11].

In this letter we focus on asymmetric bosonic dark matter and derive constraints on the DM parameters from the formation of black holes inside neutron stars. We show that for fundamental asymmetric non-interacting bosonic WIMPs, current observational data exclude all the masses from 2 keV to 16 GeV (including the range of masses 5 – 15 GeV favored by DAMA and CoGeNT). If WIMPs are composite particles made of fundamental fermions, the above constraint does not apply. However, if the compositeness scale is above  $\sim 10^{12}$  GeV (like in Grand Unified Theories (GUT)), candidates like that are again excluded in the same mass range. In addition, we constrain the case of fundamental self-interacting bosonic WIMPs. We show that if the interaction is repulsive, a vast area of self-interaction cross sections complementary to the one excluded by observations of the Bullet Cluster [20] is excluded.

*2. Bosonic Dark Matter.* Gravitational collapse of a self-gravitating lump of particles happens differently in case of bosons and fermions. In the case of fermions of mass  $m$ , a large number of particles  $N \simeq (M_{Pl}/m)^3$  is required to overcome the Fermi pressure, where  $M_{Pl}$  is the Planck mass. In the case of non-interacting bosons this number is parametrically smaller,  $N \simeq (2/\pi)(M_{Pl}/m)^2$ , since only the uncertainty principle opposes the collapse. A repulsive interaction of bosons would provide an extra pressure, so the required number of particles is larger in this case. Taking a  $\lambda\phi^4$  model as a generic example, the minimum mass of a self-gravitating lump which can form a black hole is [21]

$$M_{\text{crit}} = \frac{2M_{Pl}^2}{\pi m} \sqrt{1 + \frac{M_{Pl}^2}{4\sqrt{\pi}m} \sigma^{1/2}} \quad (1)$$

where we have expressed the result in terms of the self-interaction cross section  $\sigma = \lambda^2/(64\pi m^2)$ . Here and below we use the natural units  $\hbar = c = k_B = 1$ .

It is easy to see from eq. (1) that for cross sections  $\sigma \gg M_{Pl}^4/m^2 \sim 10^{-104} \text{ cm}^2 (m/\text{GeV})^{-2}$ , the second term

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dominates, and the minimum required mass scales (at constant  $\lambda$ ) in the same way as for the fermionic particles with a different (and potentially much smaller) coefficient. The best experimental constraints on the self-interaction cross section come from the Bullet Cluster,  $\sigma/m < 2 \times 10^{-24} \text{cm}^2/\text{GeV}$  [20].

Several conditions have to be satisfied for a gravitational collapse of WIMPs inside a neutron star to occur. Firstly, a sufficient number of DM particles must be accumulated during the lifetime of the neutron star. The accretion of WIMPs onto a typical  $1.4M_\odot$  neutron star in a globular cluster, taking into account relativistic effects, has been calculated in [9]. The total mass of accreted WIMPs is

$$M_{acc} = 4.3 \times 10^{46} \left( \frac{\rho_{dm}}{10^3 \text{GeV}/\text{cm}^3} \right) \left( \frac{t}{\text{Gyr}} \right) f \text{ GeV}, \quad (2)$$

where the “efficiency” factor  $f = 1$  if the WIMP-nucleon cross section satisfies  $\sigma_n > 10^{-45} \text{cm}^2$ , and  $f = \sigma_n/(10^{-45} \text{cm}^2)$  if  $\sigma_n < 10^{-45} \text{cm}^2$ . The condition

$$M_{acc} > M_{crit} \quad (3)$$

guarantees that the accumulated DM mass is above the critical value (1).

Secondly, the newly-formed black hole must accrete matter faster than it evaporates due to Hawking radiation. In the Bondi regime of accretion, the change of the black hole mass  $M$  with time is given by the equation

$$\frac{dM}{dt} = \frac{4\pi\rho_c G^2 M^2}{c_s^3} - \frac{1}{15360\pi G^2 M^2}, \quad (4)$$

where  $c_s$  and  $\rho_c$  are the speed of sound and the mass density of the neutron star core, respectively. The first term corresponds to the Bondi accretion while the second represents the energy loss due to Hawking radiation. Since the accretion increases while the Hawking radiation decreases as a function of  $M$ , it is the initial mass of the black hole that determines its fate. Requiring that the first term dominates when the black hole is formed gives the condition

$$M > 5.7 \times 10^{36} \text{ GeV}. \quad (5)$$

Here we have used  $\rho_c = 5 \times 10^{38} \text{GeV}/\text{cm}^3$  and  $c_s = 0.17$ . Any black hole with the initial mass satisfying eq. (5) will eventually destroy the whole star, while the smaller black holes will evaporate with no detectable effect.

The third condition necessary for the WIMP collapse into a black hole is the onset of the WIMP self-gravitation. WIMPs captured by the neutron star thermalize within a time  $t_{th} = 2 \times 10^{-5} \text{yr} (m/\text{GeV})^2$  [4, 6, 9] and concentrate in the center within the radius

$$r_{th} \simeq 2 \text{ m} \left( \frac{T_c}{10^5 \text{K}} \right)^{1/2} \left( \frac{m}{\text{GeV}} \right)^{-1/2}, \quad (6)$$

where  $T_c$  is the temperature of the star core. When their total mass  $M$  increases beyond the mass of the ordinary

matter within the same radius,

$$M > \frac{4}{3} \pi \rho_c r_{th}^3 = 2.2 \times 10^{46} \text{ GeV} \left( \frac{m}{\text{GeV}} \right)^{-3/2}, \quad (7)$$

their own gravitational field starts to dominate over that of the star and the self-gravitation regime sets in, leading to the gravitational collapse provided the condition (3) is satisfied. It can be seen from eq. (2) that (7) is satisfied if the WIMP mass is larger than  $\sim 1 \text{ GeV}$  ( $\sim 143 \text{ GeV}$ ) for  $\rho_{dm} = 10^3 \text{GeV}/\text{cm}^3$  ( $\rho_{dm} = 0.3 \text{GeV}/\text{cm}^3$ ), but not for lighter WIMPs.

However, if WIMPs are bosons they can form a Bose-Einstein condensate (BEC). Since this state is more compact, the self-gravitation in this case starts for a smaller number of particles, i.e., before the condition (7) is satisfied. The particle density required to form BEC is

$$n \simeq 4.7 \times 10^{28} \text{cm}^{-3} \left( \frac{m}{\text{GeV}} \right)^{3/2} \left( \frac{T_c}{10^5 \text{K}} \right)^{3/2}.$$

Assuming an old neutron star with a temperature  $T_c = 10^5 \text{K}$ , the number of WIMPs needed in order for BEC to form is  $N_{BEC} \simeq 2 \times 10^{36}$ . All the WIMPs accreted in excess of this value will go into the condensed state. For most of the cases of our interest, the number of accreted WIMPs will be larger than  $N_{BEC}$ , so eq. (7) has to be reconsidered.

The size of the condensed state is determined by the radius of the wave function of the WIMP ground state in the gravitational potential of the star,

$$r_c = \left( \frac{8\pi}{3} G \rho_c m^2 \right)^{-1/4} \simeq 1.6 \times 10^{-4} \left( \frac{\text{GeV}}{m} \right)^{1/2} \text{ cm}. \quad (8)$$

Substituting this size in place of  $r_{th}$  in eq. (7) we get

$$M > 8 \times 10^{27} \text{ GeV} \left( \frac{m}{\text{GeV}} \right)^{-3/2}. \quad (9)$$

In view of eq. (2), the amount of DM sufficient for WIMP self-gravitation in the condensed state can always be accumulated provided that the WIMP is heavier than  $\sim 0.1 \text{ eV}$ , which covers all cases of interest. Thus, due to the formation of BEC the requirement of self-gravitation does not provide an extra condition.

Finally, the accumulation of WIMPs may become inefficient if they may escape from the neutron star once captured, which is a danger at small WIMP masses. It can be seen from eq. (6) that for WIMP masses in the keV range the radius of the WIMP lump becomes comparable to the size of the star, so that WIMPs in the tail of the velocity distribution may escape. The rate  $F$  of WIMP evaporation can be estimated as follows [22],

$$F = n_s \left( \frac{T}{2\pi m} \right)^{1/2} \left( 1 + \frac{GMm}{RT} \right) \exp \left( -\frac{GMm}{RT} \right), \quad (10)$$

where  $T$ ,  $M$  and  $R$  are the temperature, mass and radius of the star, respectively, and  $n_s$  is the WIMP density at

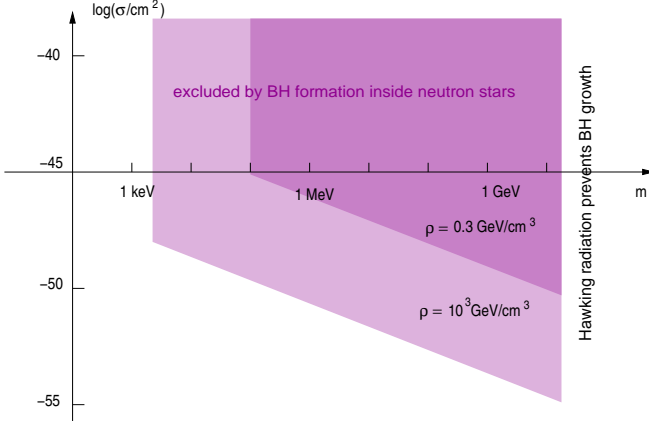


FIG. 1: The exclusion regions as a function of the DM mass and the WIMP-to-nucleon cross section for an isolated neutron star at local DM density  $\rho = 0.3 \text{ GeV/cm}^3$  (such as J0437-4715 and J0108-1431) and for a neutron star in the core of a globular cluster at  $\rho = 10^3 \text{ GeV/cm}^3$ .

the surface. Calculating  $n_s$  from the Boltzmann distribution we found that the evaporation can be safely ignored for masses larger than  $\sim 2 \text{ keV}$ .

In summary, accumulation and subsequent gravitational collapse of WIMPs captured inside a neutron star occur for WIMPs heavier than  $\sim 2 \text{ keV}$  provided the conditions (3) and (5) are satisfied. In the case of no self-interactions the collapse to a black hole inside the neutron star happens for WIMP masses  $2 \text{ keV} \lesssim m \lesssim 16 \text{ GeV}$ . The upper bound of this exclusion range is independent of the local DM density  $\rho$ , while the lower bound raises slightly at small  $\rho$ . As a function of the DM mass, the bound on the WIMP-to-nucleon cross section is  $\sigma_n > 8 \times 10^{-50} \text{ cm}^2 (\text{GeV}/m)$  for nearby isolated stars at local DM density  $\rho = 0.3 \text{ GeV/cm}^3$  and  $\sigma_n > 2 \times 10^{-54} \text{ cm}^2 (\text{GeV}/m)$  for stars in globular clusters at local DM density  $\rho = 10^3 \text{ GeV/cm}^3$ . The resulting exclusion regions are shown in Fig. 1.

Several old neutron stars have been observed, both in the vicinity of the Earth where the DM density is  $\rho \sim 0.3 \text{ GeV/cm}^3$ , and in the cores of globular clusters where the DM density may be as high as  $10^3 - 10^4 \text{ GeV/cm}^3$  [8]. Examples of nearby neutron stars are J0437-4715 [24] and J0108-1431 [25] (140 pc and 130 pc from the Earth, respectively). The examples of neutron stars in globular clusters are e.g. the pulsar B1620-26 located at the outskirts of the core of M4, and X7 from 47 Tuc [23].

In the case of a repulsive interaction, the exclusion region that follows from eqs. (3) and (5) is shown in Fig. 2. Depending on the self-interaction cross section, the constraints extend to much higher masses and are complementary to those derived from the observation of the Bullet Cluster.

**3. Composite Dark Matter.** The discussion above refers specifically to fundamental bosonic DM. If instead the latter is composite of fermions, the situation might change. There are two possibilities. Assume the total

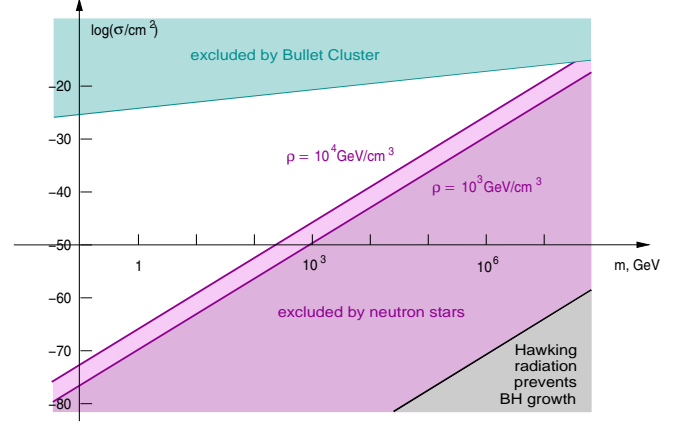


FIG. 2: Constraints on bosonic DM mass  $m$  and self-interaction cross section  $\sigma$  from observations of neutron stars in globular clusters. Excluded region (pink) is shown for two background DM densities as indicated on the plot. The cyan region shows constraints from the Bullet Cluster.

WIMP mass exceeds  $M_{\text{crit}}$ , eq. (1). As the DM lump shrinks towards its Schwarzschild radius, it might reach the density at which the mean distance between WIMPs is comparable to the scale of compositeness. At this point the Fermi pressure comes into play and might stop further collapse unless the DM lump has already reached its Schwarzschild radius.

To estimate the minimum compositeness scale  $\Lambda_{\text{crit}}$ , we express the mean distance  $d$  between WIMPs in the nearly-collapsing (i.e., having size comparable to its Schwarzschild radius) DM lump in terms of its mass  $M$ . Ignoring the numerical coefficients, we have  $d = GM^{2/3}m^{1/3}$ . Taking the mass to be equal to the critical one, eq. (1), we get

$$\Lambda_{\text{crit}} = m^{1/3} M_{\text{Pl}}^{2/3} \left( 1 + \frac{\lambda m_{\text{pl}}^2}{32\pi m^2} \right)^{-1/3}. \quad (11)$$

In the non-interacting case this gives  $\Lambda_{\text{crit}} = 2 \times 10^{12} \text{ GeV} (m/\text{GeV})^{1/3}$ , which is well below the GUT mass scale of order  $\sim 10^{16} \text{ GeV}$  for all masses of interest (cf. Fig. 2). Thus, our constraints are also valid for composite WIMPs with the compositeness scale higher than  $\sim 10^{12} \text{ GeV}$ .

**4. Discussion and conclusions.** Two remarks are in order. In the above analysis we have assumed that the black hole that is formed inside a neutron star and is not destroyed by the Hawking radiation eventually consumes the whole star. However plausible, this assumption requires some justification. In eq. (4) we have taken Bondi accretion, which is very efficient and would indeed consume the whole star much faster than in 1 Gyr (see Ref. [11] for the calculation). However, the accretion may be slowed down by the angular momentum of the star. The Bondi regime cannot be maintained if the angular momentum of the falling matter exceeds the one it would

have on the innermost stable orbit. One can show that, in the absence of momentum transfer, for a typical period of an old neutron star of the order of a second, only a small inner part of the star can be consumed in the Bondi regime. The momentum transfer has been studied in Ref. [26] in the context of ordinary stars. Rescaling the parameters to the case of a neutron star, we found that if the momentum transfer due to the viscosity is taken into account, the Bondi accretion is maintained until the black hole reaches a mass of  $\sim 10^{-7} M_{\odot}$ . From this state, with the Bondi rate the consumption of the whole star would take about 1 min. Even if the actual rate is many orders of magnitude slower, the star will definitely be destroyed within 1 Gyr.

The second remark concerns the validity of the Bondi regime at the initial stages of the black hole growth. The lightest black hole relevant for our analysis has size and Hawking temperature in the GeV range. While the fluid approximation should still be adequate at these scales because of the extremely high density of the nuclear matter, the actual parameters may differ from those used in eq. (4). This might change slightly the upper value of the exclusion mass range. The precise calculation is difficult

and goes beyond the scope of this letter.

To conclude, we have demonstrated that the existing observations of old neutron stars, both in globular clusters and in the vicinity of the Earth, exclude light non-interacting fundamental bosonic dark matter candidates in the mass range from 2 keV to about 16 GeV with WIMP-to-nucleon cross section  $\sigma_n > 8 \times 10^{-50} \text{cm}^2 (\text{GeV}/m)$ . The constraints equally apply to composite bosonic dark matter if the compositeness scale is higher than  $\sim 10^{12} \text{ GeV}$ . A wide range of masses and cross sections is also excluded for very weakly self-interacting bosonic candidates.

The work of P.T. is supported by the IISN project No. 4.4509.10 and by the ARC project “Beyond Einstein: fundamental aspects of gravitational interactions”.

**Note added:** When this paper was being finalized Ref. [27] appeared which addressed the same question. However, in Ref. [27] the Hawking evaporation of black holes was disregarded which invalidates the constraints for WIMP masses  $m > 16 \text{ GeV}$ . At smaller masses our results are somewhat different because the effect of the Pauli blocking was overestimated in Ref. [27].

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